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Correlations of current parameters with flash density from winter thunderstorms in Japan

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Abstract

In this work, Lightning Location System (LLS) data from the Japanese Lightning Detection Network (JLDN) are correlated with lightning current measurements from the New Energy and Industrial Technology Development Organization (NEDO) project which conducted lightning measurements on wind turbines during 2008-2013. The terminology of active and inactive winter thunderstorms from Fujii et al. (2013) [1] will be used as a reference to classify the discharge characteristics of the particular storm type. The results indicate that winter thunderstorms with a higher lightning activity are also characterized by higher charge, specific energy, and peak current. On the contrary, inactive winter thunderstorms produce not only fewer discharges but also show lower transferred charge amounts. Average charge and specific energy of individual flashes from very active winter thunderstorms with more than 1000 discharges are also lower compared to winter thunderstorms with 100 – 1000 discharges. Furthermore, it is shown that the height of the -10 degree isotherm is increasing with increasing lightning activity.

1 Introduction

The interaction of dry air from Siberia with the warm currents of the Sea of Japan is one of the key factors in the development of thunderclouds during the winter months which produce frequently lightning discharges on the north-western coast of Honshu Island in Japan [2]. Due to the relatively low height of the charge concentration, the electric field on ground is higher compared to thunderstorms in summer, leading to a frequent initiation of upward lightning discharges. Tall structures such as radio communication towers and wind turbines are a common starting point for these discharges due to their height and resulting electric field enhancement. Characteristics for this type of lightning are the relatively long duration, the high ratio of positive and bipolar discharges, as well as occasional high charge amounts above 300C which are lowered to the ground. Long duration lightning flashes which contain a high amount of charge expose metal conductors to deep melting on a small area whereas impulse currents with the same amount of charge create a larger affected area with relatively low penetration depth, as validated by Kern [3]. Due to this reason are tip receptors from wind turbines particularly stressed in winter lightning areas as documented by Ishii [4]. In order to gain further knowledge about lightning discharges and their resulting effects on the lightning protection system (LPS) of wind turbines, the Japanese NEDO project carried out an observation campaign at 27 wind turbines during 2008 – 2013 [5]. Current waveforms, video observation, and damage reports were collected and evaluated. More than 86% of all 834 discharges were observed from November to March [4].
Up till today, there is still a need to understand the consequences of upward lightning discharges. Local wind turbine operators in the area report repetitive damages on wind turbines which highlights the necessity of further research on this topic. Certain wind farms close to the inhabited areas in the winter lightning area in Japan are shut-off during winter lightning activity to avoid risk from detached blade parts. This leads to loss of profit for wind turbine operators and consequently restricts the potential of renewable energy in Japan.

Apart from current measurement on ground, Lightning Location Systems (LLS) provide crucial information about winter thunderstorm formation and propagation, as well as the locations where the discharge frequency peaks in form of hot-spots as described in the work from Saito and Ishii [6]. The particular threat of a winter thunderstorm to the integrity of composite structures such as radar towers or wind turbines is increased, on the one hand, by the amount of lightning attachments to the structures, and on the other hand, by the characteristic current properties of the flashes.

In this work, current measurement data from the NEDO project are compared to lightning activity determined by LLS data in order to evaluate if particular types of winter thunderstorms are especially dangerous to tall structures.

In order to structure the paper, at first details regarding the method, the area of observation and the utilized data is provided. Subsequently, correlations between the lightning parameters and the discussion on the results are presented.

2 Method

This work utilizes lightning detection data from LLS and lightning current measurement data from Rogowski coils. Both technologies are biased by shortcomings of data acquisition, especially for upward lightning with currents having low time-derivatives. This section elaborates on the limitations of the datasets and provides input for data interpretation. Beforehand, the area under investigation is illustrated and the method for the cross-correlation of the datasets is explained.

2.1 Overview

The area under investigation is on the north-west coast of Honshu Island in Japan. This area is characterized by frequent winter lightning which has been subject to previous studies for instance by Saito et al. [6] or Ishii et al. [7]. In Figure 1 the dashed circles indicate the area where the amount of daily lightning flashes are determined by means of LLS data. The red crosses are the locations of wind turbines which are used for the lightning current measurement. For the investigation, data from all sources were available in a time frame of October 2008 - March 2013.

2.2 Details regarding JLDN used in this investigation

JLDN, a LLS which provides stroke detection data, covers entire Japan, and as of December 2015, it operated six IMPACT ESP sensors, three LPATS-IV sensors, eleven LS7001, and ten TLS200 sensors. The position of the sensors can be found in Sugita and Matsui [8]. The detection efficiency of LLS is a complex subject. A comprehensive investigation of various techniques is described in [9]. Various factors such as the number of sensors, sensor baseline, network geometry, sensor sensitivity, noise handling, and dead time determine whether a flash is detected [10]. Detection efficiencies of upward lightning are substantially different from downward lightning [11]. 18% of lightning flashes observed by current measuring systems employing Rogowski coils were detected by JLDN [12].

The classification of active and inactive thunderstorms in this study is based on a fixed number of lightning detections by JLDN. As sensor technology improves, however, more flashes will be detected, so it is rather unfavorable to use fixed numbers as classification threshold. For this work, the classification aligns with previous work since the observation period and the corresponding technology are similar to those of Fujii et al. [1]: (2008 - 2009). For the analysis of JLDN data, no distinction was made between data of cloud-to-ground (CG) and intra-cloud (IC) events in the process of strokes detection since upward lightning is often missed or misclassified as IC lightning by LLS as described by Diendorfer [13].

2.3 Details regarding current measurement system

Current measurement data used in this work are based on the lightning data obtained in the NEDO project from 2008 - 2013, which measured lightning current at 27 wind turbines with Rogowski coils in Japan [5]. As indicated in Figure 1, only current measurements from 18 turbines are used. Data from the remaining 9 turbines were not considered since only few or no lightning strokes were measured at these locations. The frequency range of the Rogowski coils used was 0.1Hz to 1MHz. Upward lightning currents may be characterized by long duration continuous DC components. Therefore, the cut-off frequency of 0.1Hz was not sufficient and digital compensation down to 0.01Hz was applied to the current measurements. One example current waveform of upward lightning is illustrated in Figure 2. Specific energy and charge are derived from this waveform as indicated in Equations 1 and 2.

$$Q = \int I(t)\, dt \qquad (1)$$

$$\frac{W}{R} = \int I(t)^2\, dt \qquad (2)$$

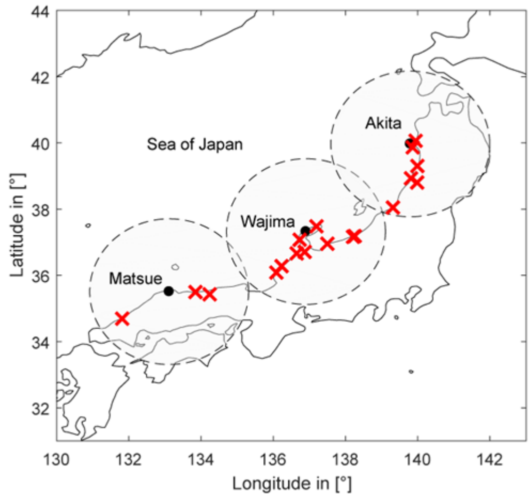


Figure 1: Geographical orientation for the study area Japan. The grey circles indicate the area for analysis of JLDN data. The red crosses mark the positions of wind turbines where lightning current measurement was performed.

2.4 Method

A flow chart of the data analysis to correlate LLS data and current measurement is indicated in Figure 3. Initially, the time reference frame of LLS data and current measurement data was aligned to the same time zone. Subsequently, each time stamp of the 814 current measurements was verified if a valid current measurement waveform was available. The timestamp was verified if it was recorded in the non-convective months November, December, January, February, or March. In the next step, the number of JLDN detections is determined in each observation area, a circle having 200km radius shown in Figure 1, six hours before and after the lightning incidence was recorded by the current measurement. In fact, this approach differs slightly from the method used in [1] and [8] since the time reference is not determined by the

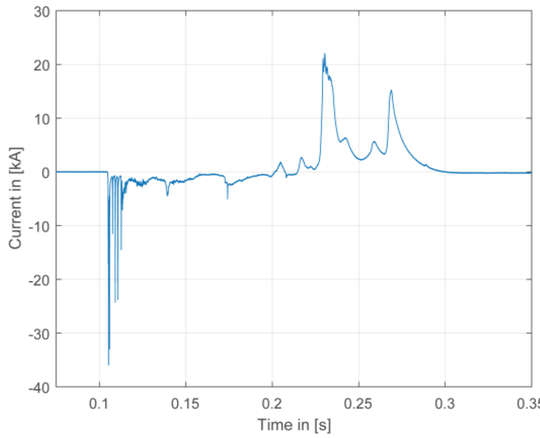


Figure 2: Measured bipolar upward lightning current waveform with Rogowski coils. 628C, 4.2MJ/Ohm, -36kA

diurnal cycle which can introduce misinterpretation if the discharge appeared around midnight. Instead, the approach of a fixed time interval provides a more accurate investigation of the lightning environment before and after a discharge was measured. With this method, the general lightning activity of the surrounding area during a winter thunderstorm was

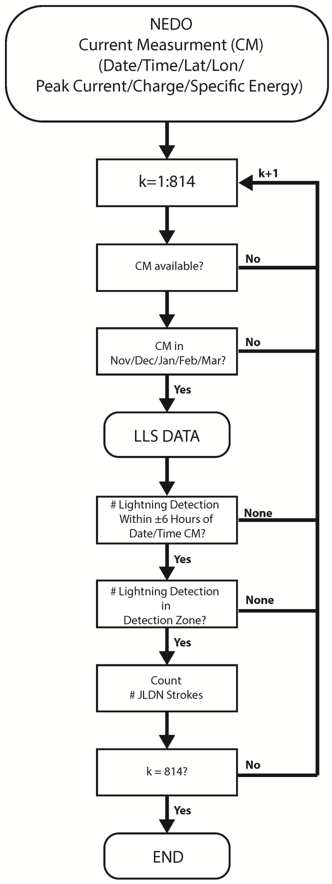


Figure 3: Flowchart to derive correlation between current parameters and LLS data (CM = Current Measurement, # = Number)

evaluated. The calculation terminates when each measured lightning discharge which is characterized by related peak current, charge and specific energy is correlated with the number of nearby detected lightning flashes.

3 Results

Figure 4 - Figure 6 illustrate the charge, specific energy and peak current distribution as a function of the number of detected LLS sources. From initially presented 834 observed lightning discharges of the NEDO report, the investigated number of discharges was reduced to 814 since only 18 instead of 27 wind turbines were investigated. Furthermore, 123 datasets did not include current measurements and where therefore excluded from the investigation. 50 events were recorded outside the specific months November - March and were consequently removed from the investigation. Additionally, at 10 events, there were no lightning events detected by JLDN in the observation area. 33 events of current measurements had a charge content of less than 3C and were removed from the investigation since flashes with such small charge content may be classified as attempted leaders instead of upward lightning discharges. The remaining 598 events are discharges in the winter months all classified as upward lightning discharges. 214 events were recorded when less than 100 lightning flashes were detected nearby, whereas in 384 events, more than or equal to 100 flashes were detected. In Figure 4, the charge distribution as a function of the number of lightning detections within six hours from the current measurement is illustrated. The vertical red line indicates 100 lightning detections, which was defined as the threshold of inactive thunderstorms as described in [1]. Apart from the individual data points, the average value of each logarithmic tile is determined and illustrated with a black line in the figure. The highest measured charge amount was 1272 C and the analyzed lowest charge amount was 3 C. The average amount of charge of one flash at storms of lightning detections below 100 is 53 C whereas it is 99 C at storms of above 100 discharges. In the charge plot two different areas are highlighted which show particularities in the data. The arrow along I indicates the tendency that the maximum measured amount of charge in flashes increases with the number of JLDN detections. The data suggests that inactive winter thunderstorms are characterized by lower amount of charge in a flash compared to active thunderstorms. The arrow along II highlights the tendency for active type thunderstorms that flashes contain statistically lower maximum charge values as more flashes are reported in the nearby environment. One data point, however, lies outside this indicated arrow II and is characterized by a charge transfer of 1272 C. The characteristic of the specific energy as a function of lightning activity is illustrated in Figure 5. The gradient of the arrows in this figure is larger compared to the charge plot.

Lightning from inactive thunderstorms tend to have lower specific energy contained in their flashes and very active thunderstorms above 600 flashes also produce flashes of reduced specific energy values.

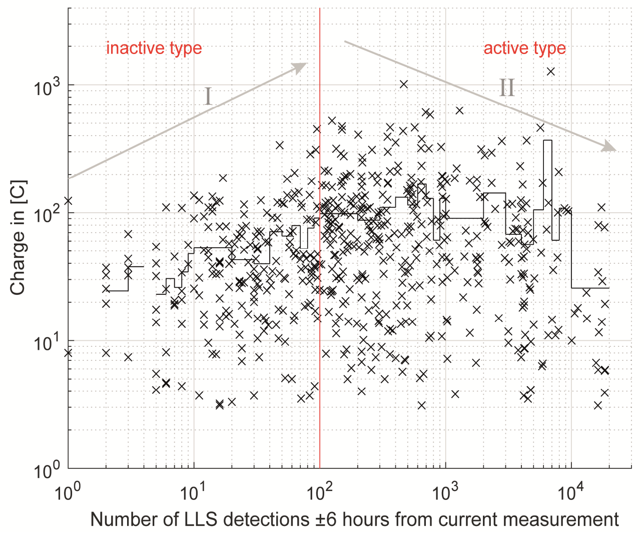


Figure 4: Flash charge as a function of measured lightning activity. Black line indicates mean value of each logarithmic tile.

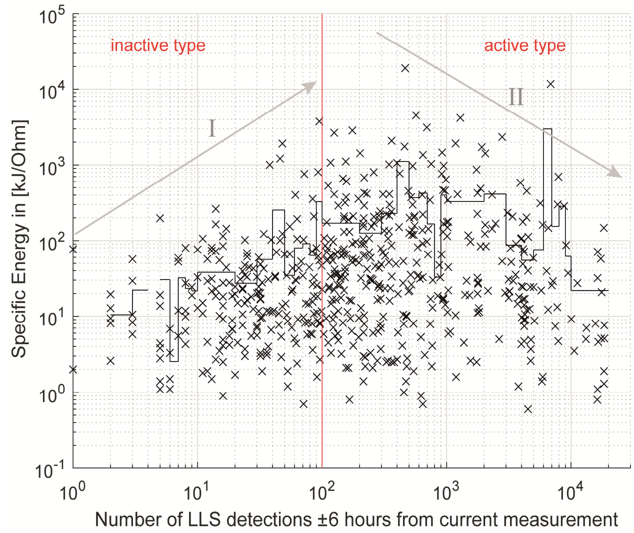


Figure 5: Specific energy as a function of measured lightning activity. Black line indicates mean value of each logarithmic tile.

Peak current distribution as a function of lightning activity is illustrated in Figure 6. Bipolar flashes are included in this analysis, and their polarities are defined by the polarity of highest peaks of currents. 140 positives and 458 negative discharges were recorded. It can be noticed that 17 out of 123 positive discharges (14%) were recorded when inactive winter thunderstorms with less than 100 detections were registered. The reduced amount of positive discharges during inactive winter thunderstorms may also be a reason for the limited charge and specific energy transfer during these storms, since positive thunderstorms are known to lower higher amount of charge to ground. In comparison, discharges of negative polarity occur in 197 out of 214 (92%) events during inactive thunderstorm activity. Inactive thunderstorm activity is evidently dominated by negative polarity events. Dependence of peak currents on activity of storms is not as clear as for the plots of charge and specific energy. Analyzed distributions of charge, specific energy and peak current for active and inactive storms are listed in Table 1, as well as the number of strokes.

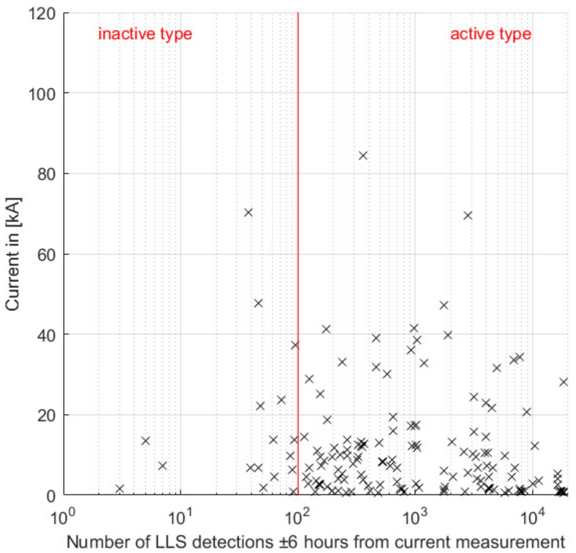
4 Discussion

From the investigation, approximately 36% (214 of 598) of all winter thunderstorms were classified as the less dangerous inactive type with lower than 100 lightning detections. The remaining 64% lightning incidences at more than 100 nearby lightning locations belong to dangerous type storms with 95 percentile values of charge and specific energy of 318 C and 1 MJ/Ohm, respectively. There is no substantial difference between the peak current values; however, inactive winter thunderstorms show reduced amount of positive discharges. Looking strictly at current parameters, the most dangerous winter thunderstorms are the ones between 400 and 3000 discharges which report the highest specific energy and charge values.

Another discussion can be taken into consideration when investigating the height of the minus ten degree isotherm which is often associated with the height of the negative

Table 1: Statistical key parameter derived for active and inactive thunderstorm type (Number = number of events, Mean = average value, 50th pct. = median value, 95th pct. = 95th percentile, Max= maximum value).

	Charge		Specific Energy		Positive Current		Negative Current	
	Inactive [C]	Active [C]	Inactive [kJ/Ohm]	Active [kJ/Ohm]	Inactive [kA]	Active [kA]	Inactive [kA]	Active [kA]
Number	214	384	214	384	17	123	197	261
Mean	53	99	75	275	15.3	12.1	-6.1	-8.7
50^{th} pct.	36	62	15	35	8.5	7.4	-3.8	-4.9
95^{th} pct.	137	322	202	1042	59.1	39.2	-18.3	-31.6
Max	450	1272	3760	19000	70.4	84.5	-31.5	-100.1



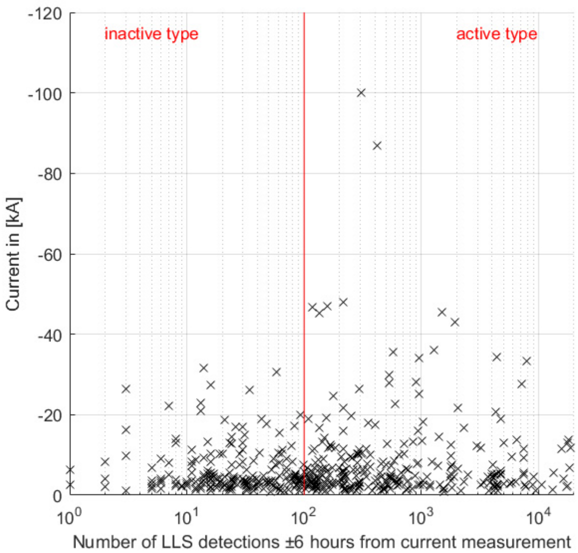


Figure 6: Positive (left) and negative (right) peak current distribution as a function of nearby lightning detections. Notice, there are only few positive registrations below 100 discharges.

charge region in the cloud. For each lightning day, the minus ten degree isotherm was extracted from the nearest radio sounding stations which was closest to the measured location of the wind turbine. As can be seen in Figure 7, the height of the minus ten degree isotherm increases with the number of LLS locations in the surrounding area. The difference between main charge region in inactive and active thunderstorms can reach up to 3 km and therefore the leader lengths must also be significantly different. This, in turn, may be reflected in different current wave shapes and different current parameters.

The results indicate that lightning flashes from winter thunderstorms of inactive type are typically characterized by lower current parameters in transferred charge and specific energy. This implicates that the threat of damage to a wind turbine blades may also be less and turning-off wind turbines during winter thunderstorms with low flash rate might be critically discussed.

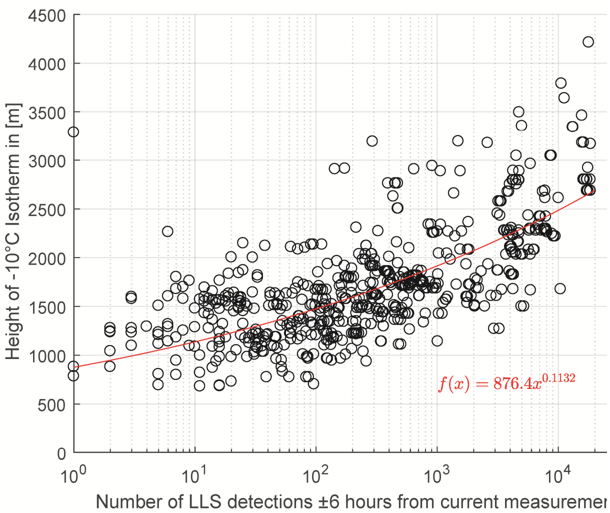


Figure 7: Height of the -10 degree isotherm dependent on lightning activity

5 Conclusion

From the investigation of current parameters as a function of lightning activity following conclusions can be drawn. Winter thunderstorms with low lightning activity are characterized by lower amount of charge and specific energy compared to winter thunderstorms with higher flash density. Therefore, not only the frequency of upward lightning attachments is limited in these storms but also the immediate threat of energetic lightning to structures is reduced. It is noticeable that positive discharges are rarely reported at inactive type thunderstorms which are commonly associated with larger charge and specific energy.

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